A Possible Future Long Baseline Neutrino and Nucleon Decay Experiment with a 100 kton Liquid Argon TPC at Okinoshima using the J-PARC Neutrino Facility

A.Badertscher[1], T.Hasegawa[2], T.Kobayashi[2], A.Marchionni[1],
A.Meregaglia[1*], T.Maruyama[2,3], K.Nishikawa[2], and A.Rubbia[1]
(1) ETH Zürich, (2) KEK IPNS, (3) University of Tsukuba

Abstract

In this paper, we consider the physics performance of a single far detector composed of a 100 kton next generation Liquid Argon Time Projection Chamber (LAr TPC) possibly located at shallow depth, coupled to the J-PARC neutrino beam facility with a realistic 1.66 MW operation of the Main Ring. The new far detector could be located in the region of Okinoshima islands (baseline $L \sim 658$ km). Our emphasis is based on the measurement of the θ_{13} and δ_{CP} parameters, possibly following indications for a non-vanishing θ_{13} in T2K, and relies on the opportunity offered by the LAr TPC to reconstruct the incoming neutrino energy with high precision compared to other large detector technologies. We mention other possible baselines like for example J-PARC-Kamioka (baseline $L \sim 295$ km), or J-PARC-Eastern Korean coast (baseline $L \sim 1025$ km). Such a detector would also further explore the existence of proton decays.

---

*Now at IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France.

1 Introduction

The "Quest for the Origin of Matter Dominated Universe" is a long standing puzzle of our physical world (see e.g. [1]). Answers to this question might come from further exploration of

- the Lepton Sector CP Violation by precise testing of the neutrino oscillation processes
  - measure precisely the δ_{CP} and the mixing angle θ_{13};
  - examine matter effect in neutrino oscillation process and possibly conclude the mass hierarchy of neutrinos.

- Proton Decay:
  - Search for $p \to \nu\ K^+$ and $p \to e\ \pi^0$ in the range $10^{34 \div 35}$ years

with assuming non-equilibrium environment in the evolution of universe.

The primary motivation of the T2K experiment* [2] is to improve the sensitivity to the $\nu_\mu \to \nu_e$ conversion phenomenon in the atmospheric regime by about an order of magnitude in the mixing angle $\sin^2 2\theta_{13}$ compared to the CHOOZ experimental limit [3]. The discovery of a non-vanishing θ_{13} angle would ascertain the 3×3 nature of the lepton flavor mixing matrix. The measurements in T2K might indicate that the θ_{13} angle is in a region where the simultaneous determination of neutrino mass hierarchy and the CP violating phase becomes possible.

The J-PARC accelerator complex which includes the 180 MeV LINAC, the 3 GeV Rapid Cycling Synchrotron (RCS) and the 30-50 GeV Main Ring Synchrotron (MR) is planned to be commissioned in 2008. The J-PARC neutrino beam facility, under construction for the T2K experiment, is foreseen to begin operation in 2009. The final goal for the T2K experiment is to accumulate an integrated proton power on target of 0.75 MW$\times 5 \times 10^7$ seconds. Within a few years of run, critical information, which will guide the future direction of the neutrino physics, will be obtained based on the data corresponding to about $1 \div 2$ MW $\times 10^7$ seconds integrated proton power on target (roughly corresponding to a 3σ discovery at $\sin^2 2\theta_{13} >$ 0.05 and 0.03, respectively) [4].

It is well documented in the literature (see e.g. Refs. [5, 6, 7]) that the most challenging task for next generation long baseline experiments is to unfold the unknown oscillation parameters $\sin^2 2\theta_{13}$, δ_{CP} and mass hierarchy, $\mathrm{sgn}(\Delta m_{31}^2)$, and from the measurement of the energy dependence of the oscillation signal to resolve the so-called problems of "correlations" and "degeneracies".

The most important experimental aspects here are the beam profile (e.g. the ability to cover with sufficient statistics the 1st maximum of the oscillation, the 1st minimum, and the 2nd maximum), the visible energy resolution of the detector, with which the neutrino energy

---

*We call T2K the approved Tokai-To-Kamioka experiment using Super-Kamiokande as far detector. New investigations or performance upgrades beyond this approved phase will presumably have a different name.

can be reconstructed, and the spectrum of the misidentified background (e.g. π^0 spectrum, etc.).

One possible approach, advocated in the literature [8, 9], is to locate a very massive coarse Water Cerenkov detector at very long baselines ($L \geq 2500$ km) from a new multi-GeV neutrino source and to detect more than one oscillation maximum. In this kind of configuration, although the oscillation peaks are well separated in energy, an important issue is the ability to subtract the backgrounds, in particular that coming from misidentified neutral current events with leading π^0's which introduce new sources of systematic errors. In order to alleviate this problem, a different approach assuming two similar far Water Cerenkov detectors, one located at Kamioka ($L \sim 295$ km) and the other in Korea ($L \sim 1000$ km) at the same OA2.5° from the J-PARC neutrino beam, was discussed in Ref. [10]. The two detectors would see the same sub-GeV neutrino beam (in fact the same as in T2K) but the different baselines would allow to study E/L regions corresponding to the 1st and 2nd oscillation maxima.

The approach of our paper is different. We consider the physics performance of a single 100 kton next generation liquid Argon Time Projection Chamber (LAr TPC) located in the region of Okinoshima islands corresponding to a (relatively modest) baseline $L \sim 658$ km. A detector in this location will automatically see the J-PARC neutrino beam at an off-axis angle of $\sim 0.8°$. As we show below, this configuration allows to study both 1st and 2nd oscillation maximum peaks with good statistics. We rely on the realistic opportunity offered by the increase of intensity of the J-PARC MR and on the higher precision of the LAr TPC than other large detectors to separate the two peaks. In addition, the π^0 background is expected to be highly suppressed thanks to the fine granularity of the readout, hence the main irreducible background will be the intrinsic ν_e component of the beam.

At this stage of our investigations, the emphasis is placed on the measurement of the θ_{13} and δ_{CP} parameters, possibly following indications for a non-vanishing θ_{13} in T2K. We also compare the possibility to determine the $\sin^2 2\theta_{13}$-δ_{CP} parameters with a single detector configuration at other possible baselines like for example the T2K (Tokai-Kamioka, OA2.5°, $L \sim 295$ km) or the Tokai-Eastern Korean coast ($L \sim 1025$ km) with an off-axis OA1.0° [11, 12]. More complete physics performance studies will be presented elsewhere.

2 A possible next step beyond T2K

If a significant ν_e signal were to be observed at T2K, an immediate step forward to a next generation experiment aimed at the discovery of CP-violation in the lepton sector would be recommended with high priority. We have conducted a case study for the discovery of lepton sector CP violation based on the J-PARC MR power improvement scenario. Naturally, next generation far neutrino detectors for lepton sector CP violation discovery will be very massive and large. As a consequence, the same detector will give us the rare and important opportunity to discover proton decay. Thus, we also discuss the proton decay discovery

potential with a huge underground detector.

Compared with the T2K experimental conditions, lepton sector CP violation discovery requires

- an improved neutrino beam condition (intensity increase, broader energy spectrum, possibly re-optimization of the focusing optics, ...);

- an improved far neutrino detector (by improvements we primarily mean increased signal reconstruction efficiency, better background separation, better energy resolution, ..., and not only its volume).

Detector improvements include

- detector technology;

- its volume;

- its baseline and off-axis angle with respect to the neutrino source.

As for the neutrino beam intensity improvement, a realistic first step power improvement scenario at J-PARC Accelerator Complex has been recently analyzed and proposed (LINAC energy is recovered to be 400 MeV, h=1 operation at RCS and 1.92 seconds repetition cycle operation at MR). As for the detector technology, we assume a 100 kton Liquid Argon Time Projection Chamber for our case study.

The effects of the CP phase δ_{CP} appear either

- as a difference between ν and $\bar{\nu}$ behaviors (this method is sensitive to the CP-odd term which vanishes for $\delta_{CP} = 0$ or 180°);

- in the energy spectrum shape of the appearance oscillated ν_e charged current (CC) events (sensitive to all the non-vanishing δ_{CP} values including 180°).

Since antineutrino beam conditions are known to be more difficult than those for neutrinos (lower beam flux due to leading charge effect in proton collisions on target, small antineutrinos cross-section at low energy, etc.), we concentrate on the possibility to precisely measure the ν_e CC appearance energy spectrum shape with high resolution during a neutrino-only run.

3   The liquid Argon Time Projection Chamber

The liquid Argon Time Projection Chamber (LAr TPC) (See Ref. [13] and references therein) is a powerful detector for uniform and high accuracy imaging of massive active volumes. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances

of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. T_0 is provided by the prompt scintillation light.

In this paper, we assume a LAr TPC detector with a mass of the order of 100 kton, for example of a kind based on the GLACIER concept [14]. Unlike other liquid Argon TPCs operated or planned which rely on immersed wire chambers to readout the ionization signals, a double phase operation with charge extraction and amplification in the vapor phase is considered here in order to allow for very long drift paths and for improved signal-to-noise ratio. We assume that successful application of such novel methods will be an important milestone in the R&D for very large LAr TPC detectors in the range of 100 kton. At this stage, a ton-scale prototype based on this scheme has been developed and is under test [15]. Challenges to realize liquid Argon TPC's with a scale relevant to this paper have been reviewed e.g. in Ref. [16].

We refer to previous physics performance studies assuming such a detector configuration [12, 17] and recall that since Liquid Argon TPC has advantages on

- good energy resolution/reconstruction,

- good background suppression,

- good signal efficiency

it is suitable for a precision measurement of the neutrino energy spectrum to extract CP information. Thus we concentrate on the ν_e appearance energy spectrum shape measurement to extract leptonic CP phase information.

4 The choice of far location: Okinoshima

The J-PARC neutrino beam line was designed and constructed in order to allow an off-axis angle with respect to Super-Kamiokande (SK) between 2.5° and 3°. A beam setup yielding an OA2.5° at SK was chosen for the T2K experiment. In this configuration, the center of the T2K neutrino beam will go through underground beneath SK, and will automatically reach the Okinoshima island region with an off-axis angle $\sim 0.8°$ and eventually the sea level east of the Korean shore with an off-axis angle $\sim 1°$. Larger off-axis angles are obtained moving inland Korea (either north, south or west). Figure 1 shows these baseline options using the same beam configuration as the T2K experiment. Parameters for different baselines and beam axes are summarized in Figure 1 and Table 1.

The neutrino flavor oscillation probability including atmospheric, solar and interference terms, as well as matter effects, can expressed using the following equation [18, 19, 11]

$$P(\nu_e \to \nu_\mu) \sim \sin^2 2\theta_{13} \cdot T_1 + \alpha \cdot \sin \theta_{13} \cdot (T_2 + T_3) + \alpha^2 \cdot T_4. \tag{1}$$
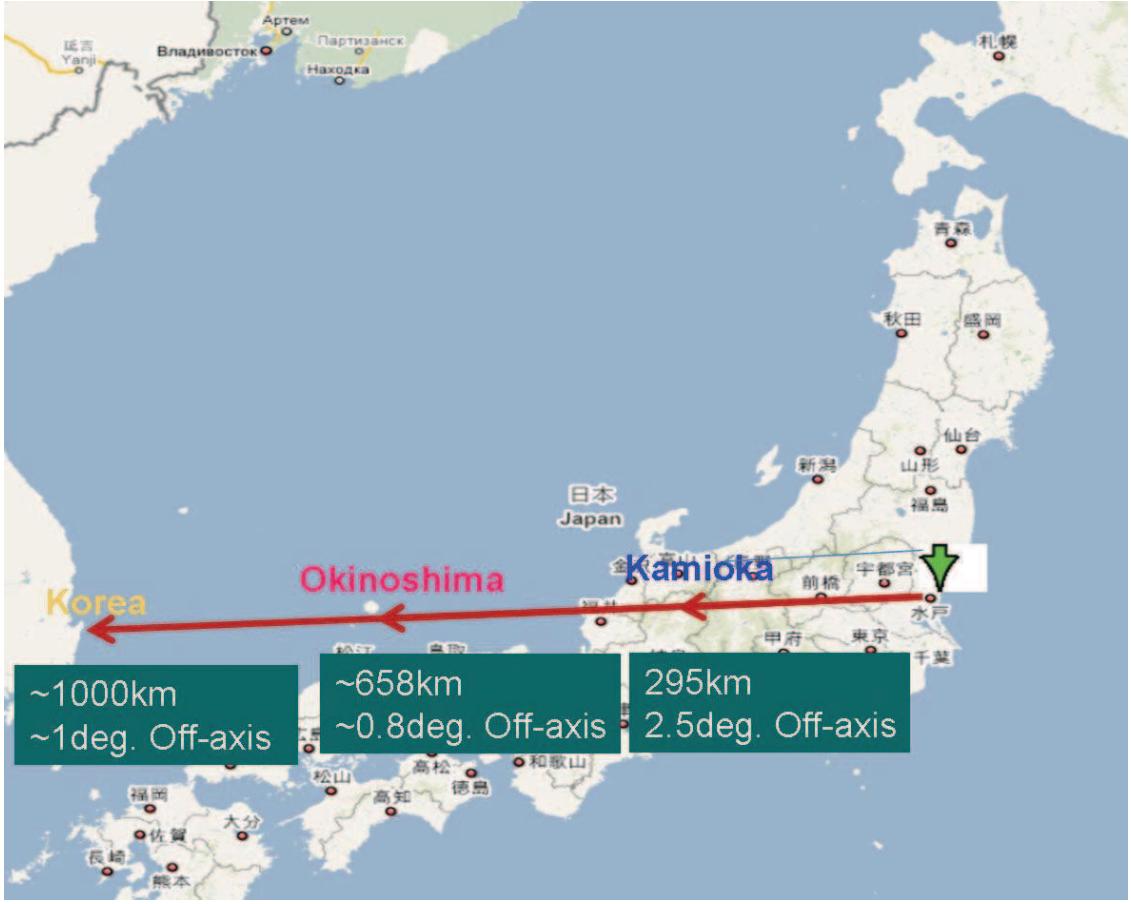
Figure 1: Possible baseline candidates for 100 kton LAr TPC detector, Kamioka (short-baseline), Okinoshima (middle-baseline) and Korea (long-baseline).

where,

$$
\begin{aligned}
T_1 &= \sin^2 \theta_{23} \cdot \frac{\sin^2[(1-A) \cdot \Delta]}{(1-A)^2} \\
T_2 &= \sin \delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \sin \Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1-A)\Delta]}{(1-A)} \\
T_3 &= \cos \delta_{CP} \cdot \sin 2\theta_{12} \cdot \sin 2\theta_{23} \cdot \cos \Delta \frac{\sin(A\Delta)}{A} \cdot \frac{\sin[(1-A)\Delta]}{(1-A)} \\
T_4 &= \cos^2 \theta_{23} \cdot \sin^2 2\theta_{12} \frac{\sin^2(A\Delta)}{A^2}.
\end{aligned}
\tag{2}
$$

where $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$, $\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$, $A \equiv \frac{2\sqrt{2}G_F n_e E}{\Delta m_{31}^2}$. $\Delta m_{31} = m_3^2 - m_1^2$, $\Delta m_{21} = m_2^2 - m_1^2$, θ_{13} is the mixing angle of the 1st and 3rd generations, while θ_{12} is that for 1st and 2nd, and θ_{23} is

Same beam configuration as T2K experiment			
	Kamioka	Okinoshima	Korea eastern shore
Baseline	295 km	∼658 km	∼1000 km
Off-axis angle	2.5°	∼0.8°	∼1.0°

Table 1: Parameters for baseline and axis with respect to beam of the candidates are summarized.

that for 2nd and 3rd generations.

The term which includes T_1 is the "atmospheric term", those including T_2 and T_3 are "interference terms", and the one that includes T_4 is the "solar term". The "interference terms" are sensitive to the δ_{CP} phase and play therefore an important role to extract the CP phase.

For definite calculations, we use the following parameters (we assume that most of these parameters will be precisely measured within the timescale of the one discussed here):

- θ_{23} is $\pi/4$.

- θ_{12} is 0.572904 rad.

- Δm_{21}^2 is 8.2×10^{-5} eV^2.

- $|\Delta m_{31}^2|$ is 2.5×10^{-3} eV^2.

- Earth density for matter effects are 2.8 g/cm^3.

- normal hierarchy is assumed unless mentioned otherwise.

Figure 2 shows the oscillation probability as a function of the E(GeV)/ L(km) (neglecting for the moment matter effects). In the plot, the mixing angle $\sin^2 2\theta_{13}$ was assumed to be 0.1. If the distance between source and detector is fixed, the curves can be easily translated to that for the expected neutrino energy spectrum of the oscillated events. As can be seen, if the neutrino energy spectrum of the oscillated events could be reconstructed with sufficiently good resolution in order to distinguish first and second maximum, useful information to extract the CP phase would be available even only with a neutrino run.

We note that the following observables depend on leptonic CP phase:

- position/height of the first oscillation maximum peak;

- position/height of the second oscillation maximum peak.

The position of the first oscillation minimum is unaffected by it (in this point all terms of the oscillation probability vanish except the solar term). To effectively experimentally study these observables, we point out that:
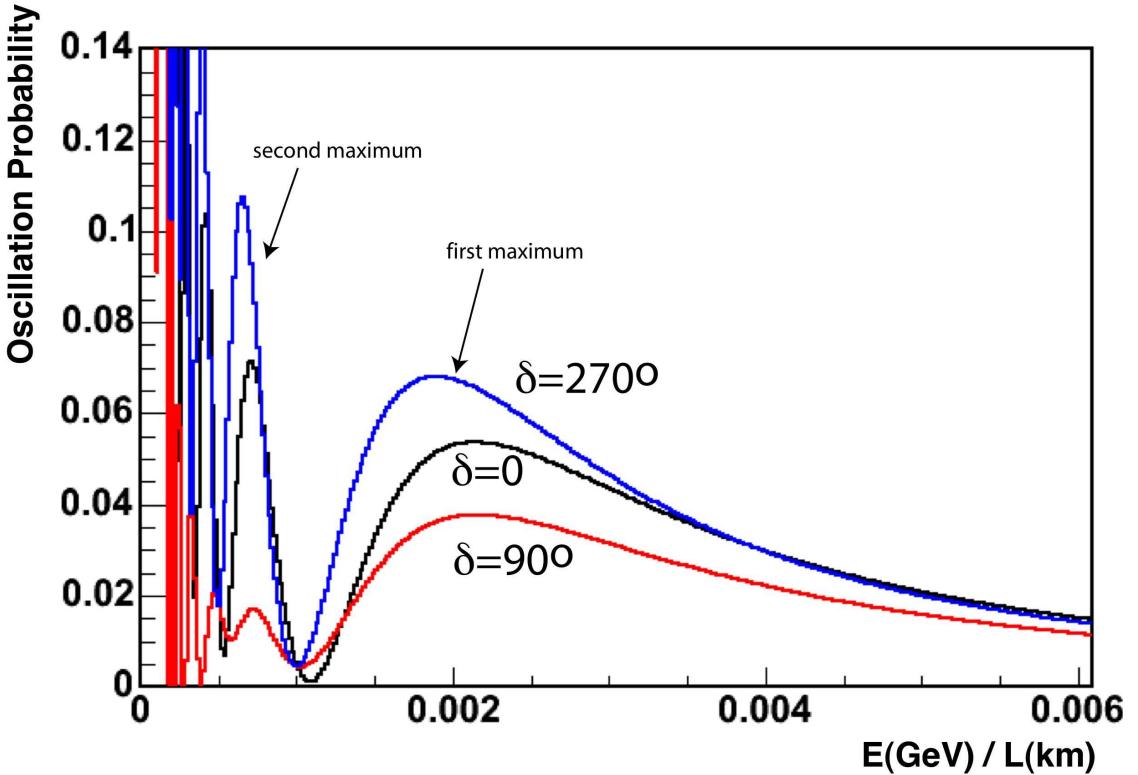
Figure 2: Probability for $\nu_\mu \rightarrow \nu_e$ oscillations as a function of the E(GeV)/L(km) for $\sin^2 2\theta_{13} = 0.1$ (for other oscillation parameters see text). Black curve shows the case for the $\delta_{CP}=0$, red shows that for $\delta_{CP}=90°$, blue shows that for $\delta_{CP}=270°$, respectively.

- the second oscillation maximum peak should end up at sufficiently high energy in order to be measurable;

- the beam should have a sufficiently wide energy range to cover the 1st and 2nd maximum;

- the neutrino flux should be maximized in order to increase as much as possible the statistical significance of the first and second maxima.

In order to cover a wider energy range, we accordingly favor a detector location which is near on-axis. If one assumes that the second oscillation maximum has to be located at an energy larger than about 400 MeV, the oscillation baseline should be longer than about 600 km. In addition, in order to collect enough statistics, we choose a baseline which is not too much longer than above stated.

Taking into account all of the above mentioned considerations, we privilege the Oki-

noshima region: placing a detector in an appropriate location on the island [†] will probe neutrino oscillations at a baseline of ~ 658 km away from the source at an off-axis angle of $\sim 0.8°$.

5   Neutrino Flux and expected Event Rates

We assume realistic parameters of the J-PARC beam after all accelerator complex upgrades described in the KEK road-map are accomplished, as follows [4]:

- The average beam power is reaching 1.66 MW;

- A total of 3.45×10^{21} POT is delivered on target per year;

- The optimal kinetic energy of the incident protons is 30 GeV.

To remain conservative, we focus on an analysis which uses a neutrino run only during five years under the best J-PARC beam assumption. An antineutrino beam (opposite horn polarity) might be considered in a second stage in order to cross-check the results obtained with the neutrino run (in particular see Section 8 on the mass hierarchy problem). The parameters of the Okinoshima location and the assumed beam are therefore as follows:

- Distance from J-PARC is 658 km;

- The axis of the beam is off by 0.76°;

- five years operation with horn setting to neutrino run.

The expected neutrino flux calculated under these assumptions is shown in Figure 3 where the curves correspond to one year run (3.45×10^{21} POT). The black, red, green, blue lines show ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ fluxes, respectively.

The interacting neutrino cross section on Argon was computed using the NUANCE programme [20]. We use the followings parameters for the cross section calculation:

- Number of protons is 18, and that of neutrons is 22.

- Medium density is 1.4 g/cm^3.

- Nucleus Fermi Gas model with binding energy of 30 MeV and Fermi momentum of 242 MeV/c.

[†]The exact location of the potential experiment in Okinoshima has not yet been investigated, but we note that the island has several hills.
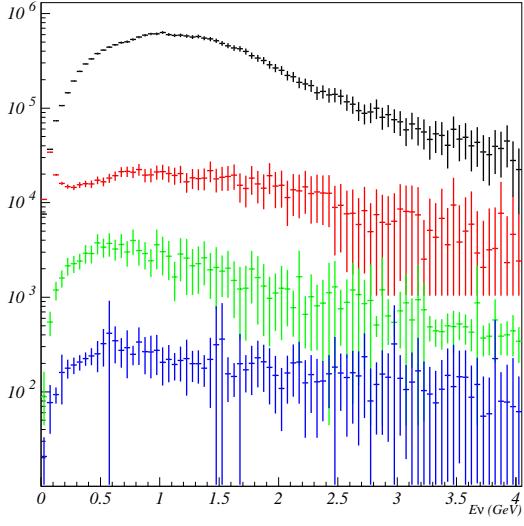
Figure 3: Calculated neutrino flux under the assumptions $(3.45 \times 10^{21}$ POT). Black shows ν_μ, red shows $\bar{\nu}_\mu$, green shows ν_e, blue shows $\bar{\nu}_e$ fluxes, respectively.
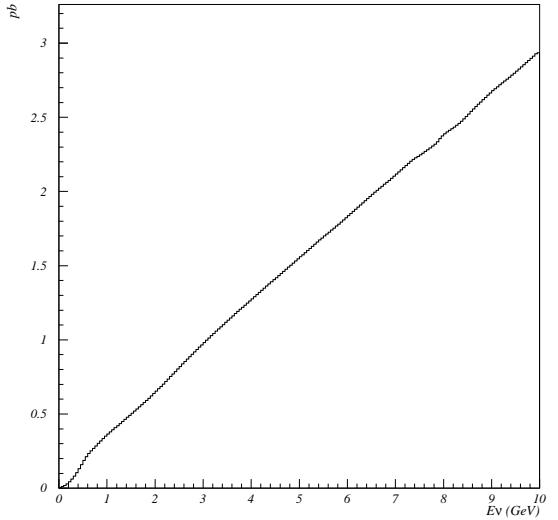

Figure 4: Calculated neutrino-Argon cross section, unit by pb. Nuclear effects are taken into account.

Taking these into account, we obtain the neutrino cross section shown in Figure 4. Table 2 shows that total number of charged current (CC) events at Okinoshima for the null oscillation case and the number of CC ν_e events from $\nu_\mu \to \nu_e$ oscillations for three different mixing angles, and in various δ_{CP} scenarios, normalized to five years neutrino run at 1.66 MW and 100 kton fiducial mass.

The number of expected events is already a good indicator of the signal, but for this analysis we use binned likelihood fitting for the energy spectrum, therefore all information including total number of events is taken into account, as described in the next section.

6   Expected Energy Spectrum of ν_e CC events

Images taken with a liquid Argon TPC are comparable with pictures from bubble chambers. As it is the case in bubble chambers, events can be analyzed by reconstructing 3D-tracks and particle types for each track in the event image, with a lower energy threshold of few MeV for electrons and few tens of MeV for protons. The particle type can be determined from measuring the energy loss along the track (dE/dx) or from topology (i.e. observing the decay products). Additionally, the electronic readout allows to consider the volume as a calorimeter adding up all the collected ionization charge. The calorimetric performance can

Events for 100 kton at Okinoshima normalized to 5 years at 1.66 MW beam power				
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
Beam components (null oscillation)	82000	750	1460	35
$\nu_\mu \rightarrow \nu_e$ oscillations				
$\delta_{CP} =$	$0°$	$90°$	$180°$	$270°$
$\sin^2 2\theta_{13} = 0.1$	2867	2062	2659	3464
$\sin^2 2\theta_{13} = 0.05$	1489	1119	1342	1908
$\sin^2 2\theta_{13} = 0.03$	942	506	829	1266

Table 2: Number of CC events at Okinoshima: beam components for null oscillation, and oscillated events in various δ_{CP} scenarios (normalized to five years neutrino run)

be excellent, as we will show in Section 10, depending on event energy and topology.

In order to understand the effect of resolution on physics performance, we show in this section the ν_e charged current (CC) event energy spectra using different simple models. One is the perfect resolution case as a reference, and others are 100 MeV/200 MeV Gaussian resolution cases for more realistic cases. This "resolution" should include neutrino interaction effects as well as detector resolution. Possible smearing or backgrounds affecting the measurement of the neutrino energy spectrum are listed below subdivided into 4 classes:

- Neutrino interaction:

    - Fermi motion and nuclear binding energy,
    - Nuclear interactions of final state particles within the hit nucleus (FSI),
    - Vertex nuclear remnant effects (e.g. nuclear break-up signal),
    - Neutral Current (NC) π^0 event shape including vertex activity.

- Detector medium:

    - Ionization processes,
    - Scintillation processes,
    - Correlation of between amount of charge and light,
    - Charge and light quenching,
    - Hadron transport in Argon and secondary interactions,
    - Charge diffusion and attenuation due to impurity attachment.

- Readout system including electronics system:

    - signal amplification or lack thereof,

11

– signal-to-noise ratio,

– signal shaping and feature extraction.

- Reconstruction:

    – Pattern recognition

    – Background processes (NC π^0, ν_μ CC, ...) and their event shape

    – Particle identification efficiency and purity

Very few real events in liquid Argon TPCs have so far been accumulated to allow a full understanding of these complex effects and their interplay. The only sample comes from a small 50 lt chamber developed by the ICARUS Collab. and exposed to the CERN WANF high energy neutrino beam which collected less than 100 quasi-elastic events [21].

It is clear that the energy resolution will depend on several detector parameters, including the readout pitch, the readout method chosen and on the resulting signal-over-noise ratio ultimately affecting the reconstruction of the events. We therefore stress that significantly improved experimental studies with prototypes exposed to neutrino beams of the relevant energies and sufficient statistics are mandatory to assess and understand these effects. In the meantime, we give in Section 10 preliminary estimates for potentially achievable energy resolutions in a liquid Argon medium. The results are based on full GEANT3 [22] simulation of the energy deposited by final state particles in the detector volume, however do not include all possible contributing effects.

Figure 5 shows the energy spectra of electron neutrino at the cases of δ_{CP} equal $0°$, $90°$, $180°$, $270°$, respectively. Shaded region is common for all plots and it shows the background from beam ν_e. Here perfect resolution is assumed for reference to later cases.

If we smear the energy spectra shown in Figure 5 with Gaussian of sigma equals to 100 or 200 MeV independent from original neutrino energy, we obtain spectra shown in Figures 6 and 7. As seen easily, an energy resolution below 100 MeV is crucial since the robustness of the neutrino oscillation is directly determined by the visible second oscillation peak around 400 MeV in the energy spectrum. In 200 MeV resolution case, the second peak is hidden by the smearing of the 1st oscillation maximum peak.

7 Oscillation parameters measurement from energy spectrum analyses

Assuming all others were measured very precisely, there are only two free parameters $\sin^2 2\theta_{13}$ and δ_{CP} to be fitted using the energy spectra. As shown in Figure 2, the value of δ_{CP} varies the energy spectrum, especially the first and the second oscillation peaks (heights and positions), therefore comparison of the peaks determine the value δ_{CP}, while the value of $\sin^2 2\theta_{13}$ changes number of events predominantly.

To fit the free parameters, a binned likelihood method is used. The Poisson bin-by-bin probability of the observed data from the expected events (for an assumed pair of values
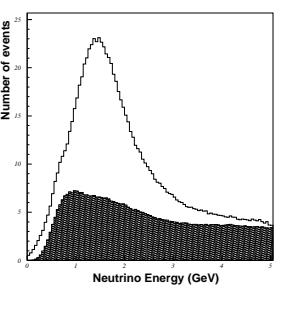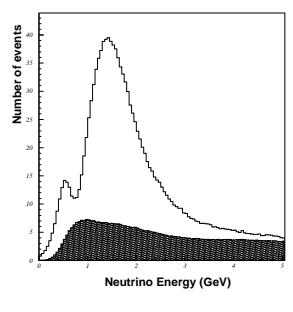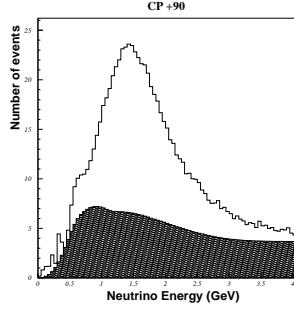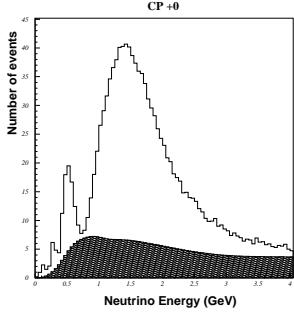
Figure 5: Energy spectra at $\sin^2 2\theta_{13}$=0.03 case, but $\delta_{CP} = 0°$ (top-left), 90° (right-top), 180° (left-bottom), 270° (right-bottom) cases.
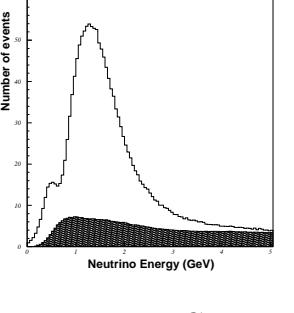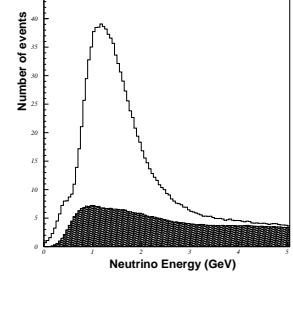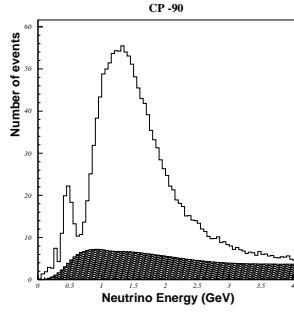
Figure 6: Energy spectra assuming Gaussian 100 MeV smearing. $\delta_{CP} = 0°$ (top-left), 90° (right-top), 180° (left-bottom), 270° (right-bottom) cases.

$(\sin^2 2\theta_{13},\ \delta_{CP}))$ is calculated. The fit procedure is validated by testing the result on a pseudo-experiment. Figure 8 shows one typical pseudo-experiment for the perfect resolution case (with δ_{CP} equals to 0, and $\sin^2 2\theta_{13}$ equals to 0.1). Best fit gives reasonable result.

At this stage, we only take statistical uncertainty into account for the fitting, thus other systematic uncertainties like far/near ratio, beam ν_e shape, energy scale, and so forth are not considered. Also, oscillated signal and beam ν_e are only accounted in the fit, i.e. other background like neutral current π^0 or beam $\bar{\nu}_e$ contamination is assumed to be negligible compared to beam ν_e contamination.

As a reference, we first extract allowed regions in the perfect resolution case (See Figure 9). Twelve allowed regions are overlaid for twelve true values, $\sin^2 2\theta_{13}$=0.1, 0.05, 0.02, and δ_{CP}=0°, 90°, 180°, 270°, respectively. The δ_{CP} sensitivity is 20~30° depending on the true δ_{CP} value.

Allowed regions are then extracted for 100 and 200 MeV resolution cases. The used energy spectra are same as Figures 6 and 7. Results are shown as Figures 10 and 11.

One obvious but important issue to be pointed out is the robustness of the fitting.The fit procedure shows that results could also be extracted with the 200 MeV resolution: this result is as expected statistically; however, we stress that in this case there is no second oscillation maximum peak visible in Figure 7. Hence, we think it is mandatory to keep an energy resolution less than 100 MeV as goal for the credibility of this experiment.
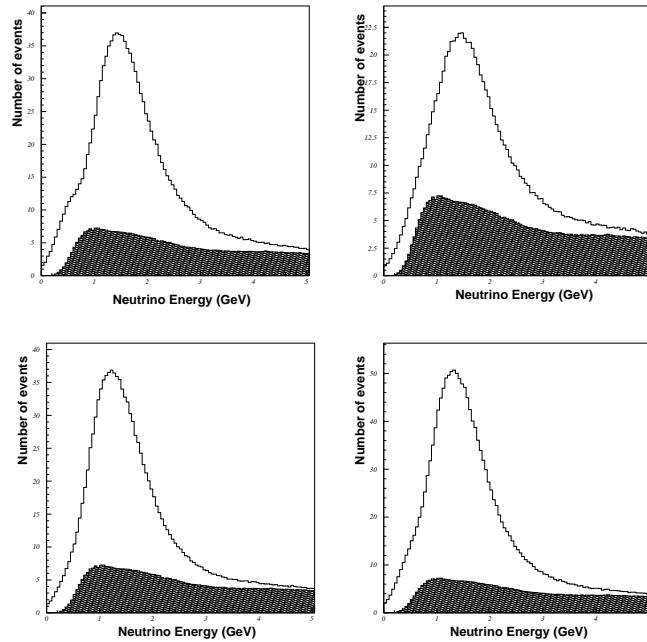
Figure 7: Energy spectra assuming Gaussian 200 MeV smearing. $\delta_{CP} = 0°$ (top-left), $90°$ (right-top), $180°$ (left-bottom), $270°$ (right-bottom) cases.

8 Investigation of mass hierarchy

The influence of matter on neutrino oscillations was first considered by Wolfenstein [23]. As is well-known (although never directly experimentally verified), oscillation probabilities get modified under these conditions. Matter effects are sensitive to the neutrino mass ordering and different for neutrinos and antineutrinos. As mentioned earlier, we consider in this paper the possibility of a neutrino-only run. Hence, we briefly address in this section the question of normal hierarchy (NH) versus inverted hierarchy (IH). Since we are focusing on the potential discovery of CP-violation in the leptonic sector, our discussion is geared towards possible ambiguities that would arise if the mass hierarchy was unknown.

Indeed, Figure 12 illustrates the results of a fit of a pseudo-data with NH by both NH (black) and IH (red) hypotheses, assuming only the neutrino run. The best fit likelihood value with one assumed hierarchy is used to calculate the likelihood variation ΔL for both hierarchies. One could claim that CP-violation is discovered if the experimental results of a given experiment exclude the δ_{CP} phase to be either 0 or 180°. Hence, the danger is that the lack of knowledge of the mass hierarchy (or rather the "wrong" choice in hypothesis when selecting the hierarchy in the fit of the data), gives a result for δ_{CP} consistent with either 0 or 180°. On the other hand, if fits of a given experiment with both assumed hierarchies provide neither 0 nor 180°, one can declare "discovery" although the mass hierarchy could not be
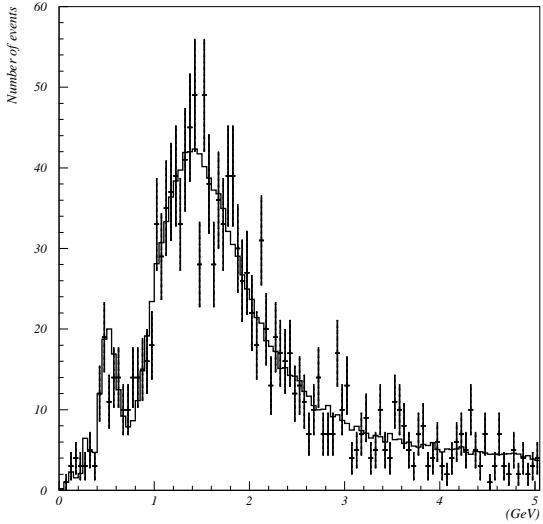
Figure 8: Typical one pseudo-experiment to show the validity of the fitting. Histogram shows the best-fit (best oscillation shape + background), and the crosses show the pseudo-data.

determined. Alternatively, if it turned out in the actual experiment that one of results of the fit is consistent with $\delta_{CP} = 0$ or 180°, one would still have the possibility to consider an anti-neutrino run in order to solve this ambiguity.

Our results indicate that CP-violation would be unambiguously discovered under our assumption for true values of δ_{CP}'s in the region of 90° and 270°. Alternatively, in case of true values of δ_{CP}'s near 0° or 180° an antineutrino flux would help untangle the two solutions if the neutrino mass hierarchy was unknown.

9   Expected sensitivity to $\sin^2 2\theta_{13}$

Although this paper has focused on the possibility to measure the $\sin^2 2\theta_{13}$ and δ_{CP} oscillation parameters, it is instructive to estimate the sensitivity of the potential setup in the case of negative result from T2K. The corresponding sensitivity to discover θ_{13} in the true ($\sin^2 2\theta_{13}, \delta_{CP}$) plane at 90% C.L. and 3σ is shown in Figure 13, where we assumed 5 years of neutrino run comparing the 100 kton LAr at Okinoshima with increased statistics in SK at Kamioka and a potential 20 kton LAr at Kamioka.

In order to discover a non-vanishing $\sin^2 2\theta_{13}$, the hypothesis $\sin^2 2\theta_{13} \equiv 0$ must be excluded at the given C.L. As input, a true non-vanishing value of $\sin^2 2\theta_{13}$ is chosen in the
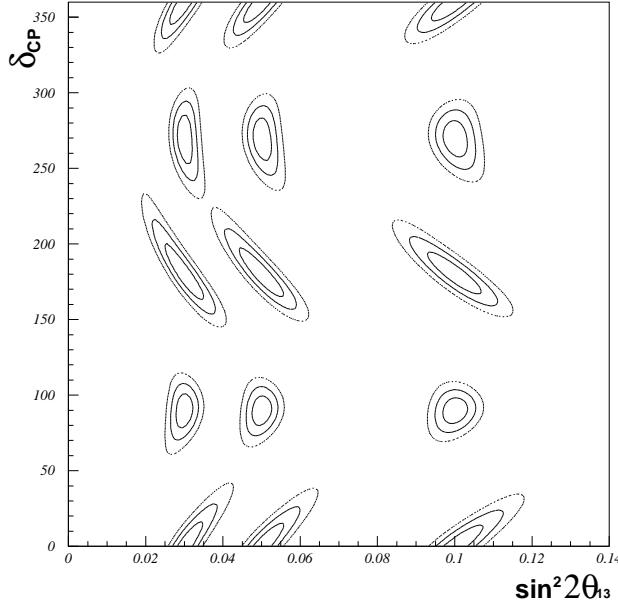
Figure 9: Allowed regions in the perfect resolution case. Twelve allowed regions are overlaid for twelve true values, $\sin^2 2\theta_{13}$=0.1, 0.05, 0.02, and δ_{CP}=0°, 90°, 180°, 270°, respectively.
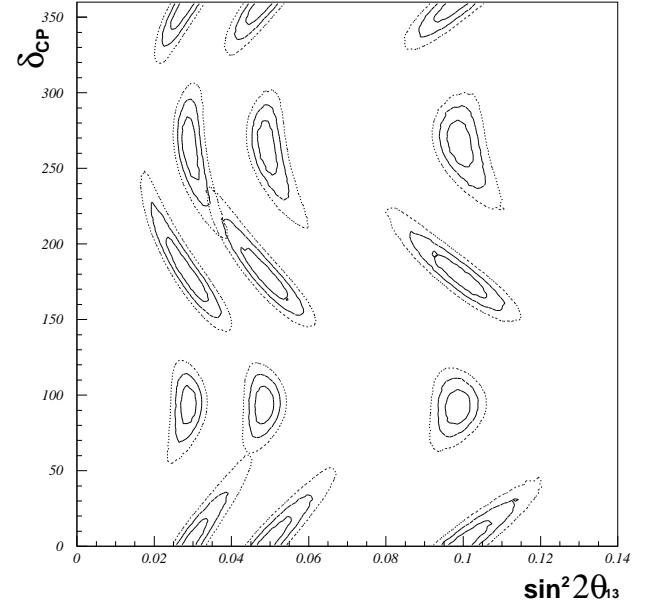
Figure 10: Allowed regions in the 100 MeV resolution (Gaussian sigma) case. Twelve allowed regions are overlaid for twelve true values, $\sin^2 2\theta_{13}$=0.1, 0.05, 0.02, and δ_{CP}=0°, 90°, 180°, 270°, respectively.

simulation and a fit with $\sin^2 2\theta_{13} = 0$ is performed, yielding the "discovery" potential. This procedure is repeated for every point in the $(\sin^2 2\theta_{13}, \delta_{CP})$ plane.

At the 3σ C.L. the sensitivity of the T2K experiment is 0.02 [2]. Continuing to collect data at SK with an improved J-PARC neutrino beam for another 5 years would improve the T2K sensitivity by a factor ~ 2. In comparison, our simulations indicate that a 20 kton LAr TPC is expected to perform better than this although the masses are comparable, since the signal efficiency is higher than SK and the NC background is assumed to be negligible contrary to SK. Even better, a 100 kton LAr TPC at Okinoshima would further improve the sensitivity by about a factor six compared to SK at Kamioka (or a factor 10 compared to T2K), thanks to its bigger mass, increased cross-section at higher energies and reduced off-axis angle, although the neutrino fluxes at the same off-axis angle would be reduced by a factor $\simeq 5$ because of the longer baseline.
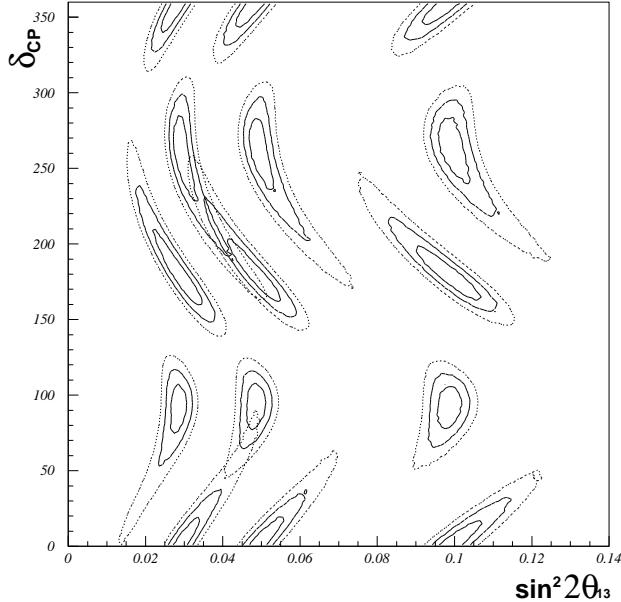
Figure 11: Allowed regions in the 200 MeV resolution (Gaussian sigma) case. Twelve allowed regions are overlaid for twelve true values, $\sin^2 2\theta_{13}$=0.1, 0.05, 0.02, and δ_{CP}=0°, 90°, 180°, 270°, respectively.

10   Neutrino energy resolution in a LAr medium

As mentioned previously, the neutrino energy resolution expected in LAr medium depends on several parameters and their interplay that ultimately need to be measured experimentally.

In principle, energy and momentum conservation allow to estimate the incoming neutrino energy in the detector via a precise measurement of decay products, with the exception of the smearing introduced by Fermi motion and other nuclear effects (nuclear potential, re-scattering, absorption, etc.) for interactions on bound nucleons. In this section, we try to estimate the smearing introduced by these effects with the help of exclusive neutrino event final states distributed with the Okinoshima flux and generated with the GENIE MC [24] subsequently fully simulated with GEANT3.

Nuclear effects in neutrino interactions can be roughly divided into those of the nuclear potential and those due to reinteractions of decay products. Bound nucleons and other hadrons in nuclei are subject to a nuclear potential. The Fermi energy (or momentum) must be calculated from the bottom of this nuclear potential well, and the removal of a nucleon from any stable nucleus is always an endothermic reaction. When hadrons are produced in the nucleus, some energy is spent to take it out of this well: for a nucleon, the minimum energy is given by the nucleon separation energy (around 8 MeV), and corresponds to a
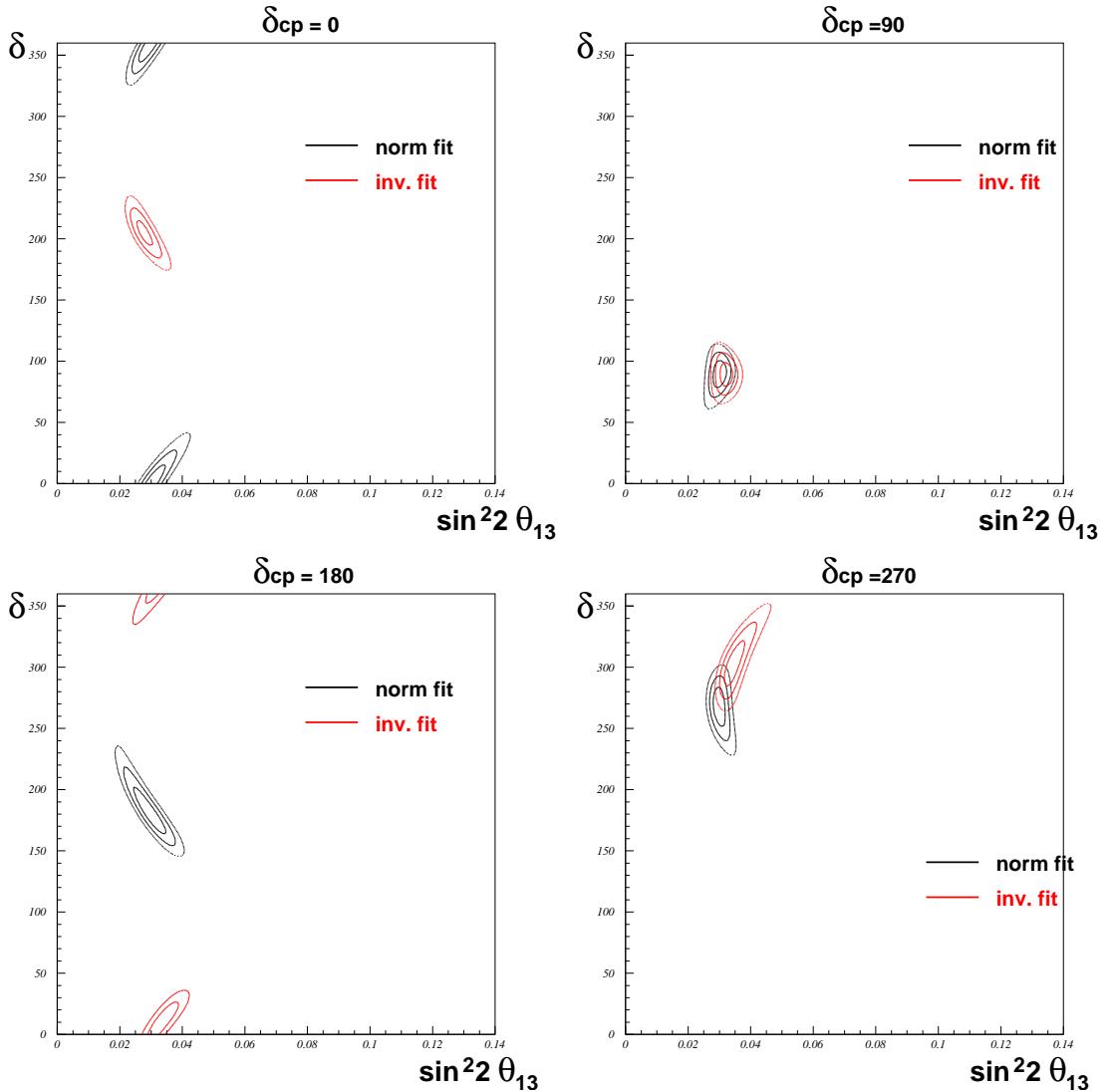
Figure 12: Mass hierarchy investigation with neutrino run only. If fits with both hierarchy hypotheses provide neither 0 nor 180°, one can declare discovery of CP violation in the leptonic sector. If any of the fits results in a δ_{CP} of 0 or 180°, then an anti-neutrino run could be envisaged.
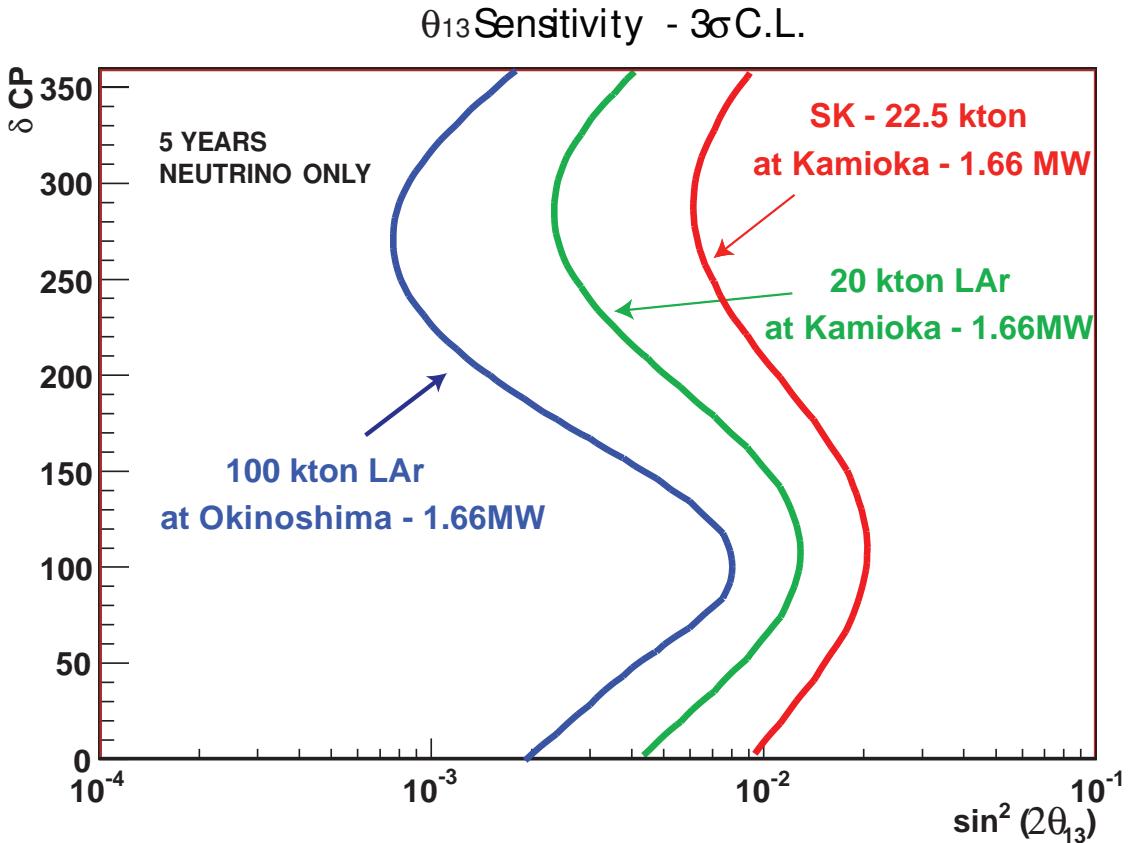
Figure 13: Sensitivity to $\sin^2(2\theta_{13})$ for 5 years of neutrino run comparing 100 kton LAr at Okinoshima with SK at Kamioka and 20 kton LAr at Kamioka.

nucleon at the Fermi surface. In this case, the daughter nucleus is left on its ground state. More deeply bound nucleons, leaving a hole in the Fermi sea, correspond to an excitation energy of the daughter nucleus, and an additional loss of energy of the final state products. This energy is then spent in evaporation and/or gamma deexcitation. Thus, the energy of the final state products is expected to be always slightly smaller than for interactions on free nucleons, and spread over a range of about 40 MeV. Correspondingly, the Fermi momentum is transferred to the decay products and compensated by the recoil of the daughter nucleus. Additional momentum distortions come from the curvature of particle trajectories in the nuclear potential.

Reinteractions in the nuclear medium also play an important role. Interaction products can lose part of their energy in collisions, or even be absorbed in the same nucleus where they have been created. This is particularly true for pions, that have an important absorption cross section on nucleon pairs, while kaons have smaller interaction probability.

Once final state products have exited the nucleus, they will propagate in the medium
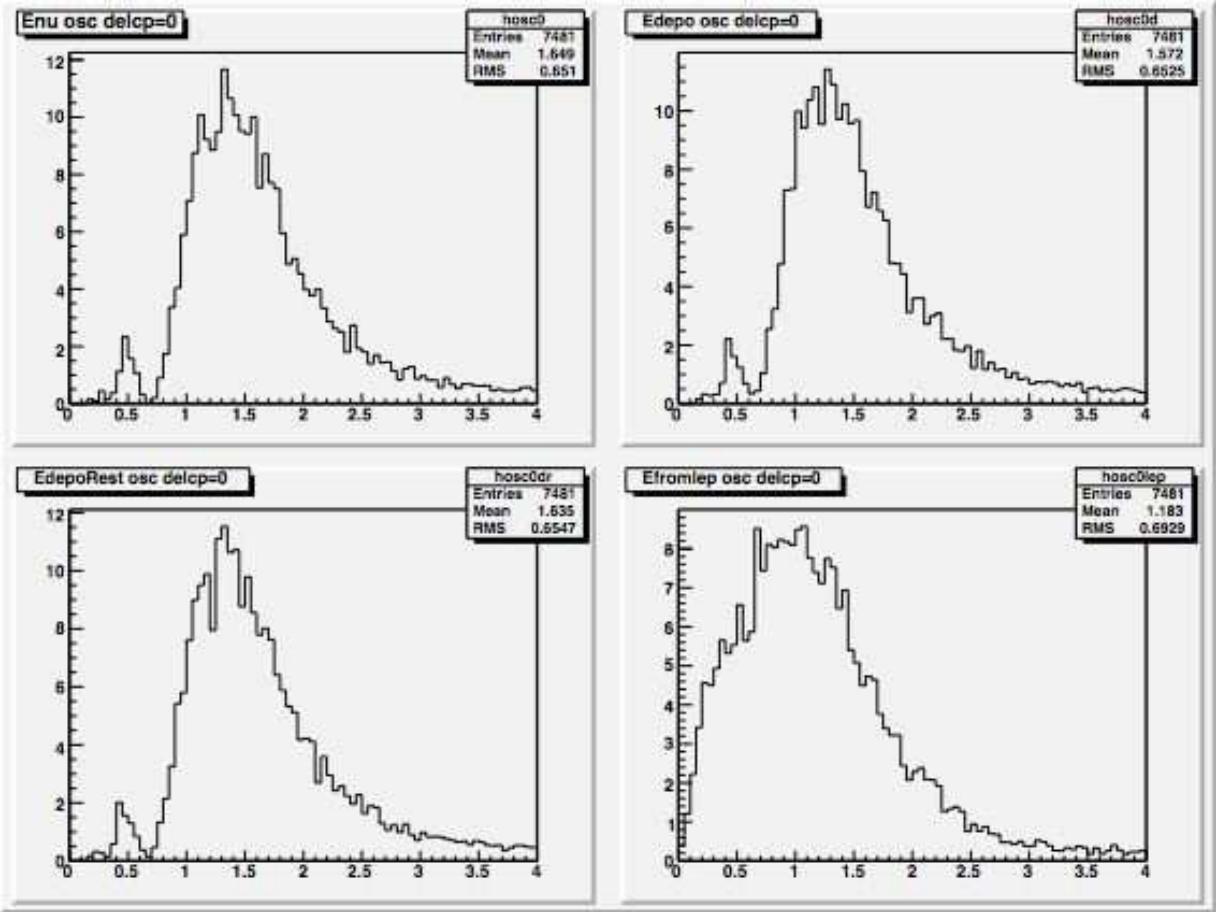
Figure 14: Full GEANT simulations of the reconstructed neutrino energy spectra from detailed event simulation (see text) for neutrino oscillations with $\delta_{CP} = 0°$: perfect reconstruction (top-left), LAr using deposited energy(right-top), ibid but with charged pion mass correction (left-bottom) using final state lepton only (like in WC) (right-bottom) cases.

with the possibility that further interactions occur.

In the case of the liquid Argon TPC, the medium is fully homogeneous and the detector is fully active. All deposited energy in the medium (above a certain threshold) will be eventually collected. Several methods can be adopted to reconstruct the neutrino energy and we list in the following three:

1. **Final state lepton:** this method, traditionally used in large Water Cerenkov detectors like Kamiokande, IMB or SK, relies on the precise measurement of the energy and direction of the outgoing lepton and kinematically constrains the incoming neutrino

20

energy by assuming a quasi-elastic configuration:

$$E_\nu = \frac{ME_\ell - m_\ell^2/2}{M - E_\ell + p_\ell \cos\theta_\ell}$$

where E_ℓ, p_ℓ and $\cos\theta_\ell$ are the energy, momentum and scattering angle of the outgoing lepton. This method is sensitive to the final state configuration and to Fermi motion (up to $\simeq 240$ MeV/c) which randomizes the direction of the outgoing lepton.

2. **Momentum conservation:** neglecting the incoming neutrino mass, one obtains

$$E_\nu = |\vec{P}_\nu| = |\vec{p}_\ell + \sum_h \vec{p}_h - \vec{P}_F|$$

where $\vec{p}_\ell$ is the momentum of the outgoing lepton, $\vec{p}_h$ is the momentum of the outgoing hadron h and $\vec{P}_F$ is the Fermi motion of the hit nucleon (up to $\simeq 240$ MeV/c). This method is also sensitive to Fermi motion since the recoiling remnant hit nucleus (with momentum $-\vec{P}_F$) is not measured [‡].

3. **Energy conservation:** using a calorimetric approach, one can sum the deposited energies of all outgoing particles. In a tracking-calorimeter this is obtained by summing the dE/dx measurements along each ionizing track to obtain the associated kinetic energies $T \equiv \int (dE/dx)dx$. One should identify final state particles in order to take into account their rest masses. This method is sensitive to the nuclear binding energy of the decay products and is intrinsically more precise than the above method relying on momenta for the energies considered here. Mathematically one can write this result as:

$$\begin{aligned}
E_\nu &= E_{tot} - M = E_\ell + \sum_h E_h - M = E_\ell + \sum_h (T_h + m_h) - M \\
&= E_\ell + T_N + \sum_{\pi^\pm} (T_{\pi^\pm} + m_{\pi^\pm}) + \sum_\gamma E_\gamma + ...
\end{aligned} \tag{3}$$

All methods are sensitive to potential re-interactions of the outgoing hadrons within the nucleus. In order to estimate the potential of a fully homogeneous and sensitive medium like the liquid Argon TPC, we performed full simulations of neutrino interactions: the event 4-vector are generated with the GENIE MC and final state particles (after nuclear reinteraction) were propagated through the liquid Argon medium with GEANT3. The geometry of the setup is an infinite LAr box and at this stage we have neglected charge quenching (i.e.

[‡]We point out that if one uses the knowledge on the direction of the incoming neutrino, the total (missing) transverse momentum can be kinematically constrained to zero, thereby providing a handle compensate for the transverse component of the Fermi motion. The longitudinal component of the momentum, which is not negligible at low neutrino energies, remains however undetermined.

we assume a linear response to dE/dx). We also assume a 100% efficiency to identify final state charged pions.

The achievable incoming neutrino energy resolution in the liquid Argon medium has been estimated using ν_e CC events distributed with the ν_μ flux expected at the Okinoshima location. The results, using the energy conservation method, are shown in Figure 14.

11   Other baseline options

Although Okinoshima looks a very good candidate as mentioned so far, the favorable geography would allow, in principle, for a few baseline candidates for the detector locations; Kamioka for a relatively "short" baseline, Okinoshima for a medium baseline and Korea for the longest baseline. It is worthwhile to compare the physics potential at Okinoshima with other scenarios with the same strategy and same assumed beam conditions, i.e. five years neutrino run at 1.66 MW.

Figure 15 illustrates the analyzed allowed regions using each option. A perfect resolution was assumed here to directly compare the physics potential of the various sites. As seen, sensitivity of δ_{CP} is similar between Okinoshima and Korea, but that in Kamioka is much worse than others. This indicates the analysis strategy using only neutrino run is not suitable for Kamioka case, as was expected since the OA2.5° available at Kamioka does not allow to cover 1st and 2nd oscillation maxima peaks. As for the sensitivity of the $\sin^2 2\theta_{13}$, Okinoshima is better than Korea, due to the increased statistics at the shorter baseline.
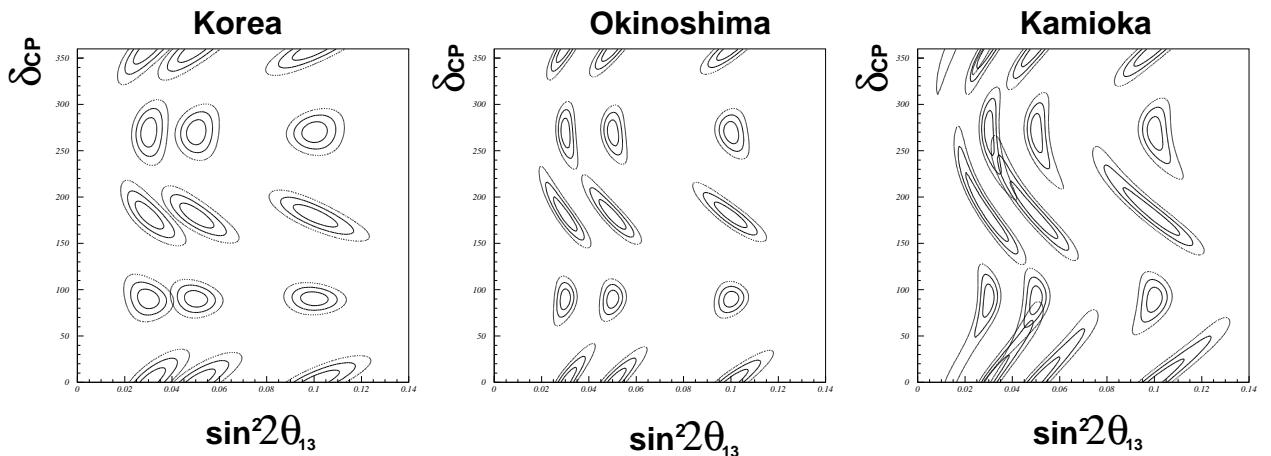

Figure 15:   Allowed regions if the location of the 100 kton LAr TPC were at Kamioka, Okinoshima or Korea, assuming the T2K beam optics is kept. Perfect resolution is assumed to illustrate the physics potential from each site selection.

12 Proton Decay Discovery Potential

Grand Unification of the strong, weak and electromagnetic interactions into a single unified gauge group is an extremely appealing idea [25, 26] which has been vigorously pursued theoretically and experimentally for many years. The detection of proton or bound-neutron decays would represent its most direct experimental evidence. The physics potentialities of very large underground Liquid Argon TPC was recently carried out with detailed simulation of signal efficiency and background sources, including atmospheric neutrinos and cosmogenic backgrounds [27]. It was found that a liquid Argon TPC, offering good granularity and energy resolution, low particle detection threshold, and excellent background discrimination, should yield very good signal over background ratios in many possible decay modes, allowing to reach partial lifetime sensitivities in the range of $10^{34} - 10^{35}$ years with exposures up to 1000 kton×year, often in quasi-background-free conditions optimal for discoveries at the few events level, corresponding to atmospheric neutrino background rejections of the order of 10^5. Multi-prong decay modes like e.g. $p \rightarrow \mu^- \pi^+ K^+$ or $p \rightarrow e^+ \pi^+ \pi^-$ and channels involving kaons like e.g. $p \rightarrow K^+ \bar{\nu}$, $p \rightarrow e^+ K^0$ and $p \rightarrow \mu^+ K^0$ are particularly suitable, since liquid Argon imaging provides typically an order of magnitude improvement in efficiencies for similar or better background conditions compared to Water Cerenkov detectors. Up to a factor 2 improvement in efficiency is expected for modes like $p \rightarrow e^+ \gamma$ and $p \rightarrow \mu^+ \gamma$ thanks to the clean photon identification and separation from π^0. Channels like $p \rightarrow e^+ \pi^0$ or $p \rightarrow \mu^+ \pi^0$, dominated by intrinsic nuclear effects, yield similar efficiencies and backgrounds as in Water Cerenkov detectors. Thanks to the self-shielding and 3D-imaging properties of the liquid Argon TPC, the result remains valid even at shallow depths where cosmogenic background sources are important. In conclusion, a LAr TPC would not necessarily require very deep underground laboratories even for high sensitivity proton decay searches.

Once again, we stress the importance of an experimental verification of the physics potentialities to detect, reconstruct and classify events in the relevant GeV energy range. This experimental verification will require the collection of neutrino event samples with high statistics, accessible e.g. with a detector located at near sites of long baseline artificial neutrino beams.

13 Conclusions

In this paper, we have reported our case study for a new future long baseline neutrino and nucleon decay experiment with a 100 kton Liquid Argon TPC located in the region of Okinoshima using the J-PARC Neutrino Facility.

Our study assumes a realistic upgrade of the J-PARC Main Ring operation yielding an average 1.66 MW beam power for neutrinos coupled to the new far detector at Okinoshima, which would then see the beam at an off-axis angle of $\simeq 1°$ and at a baseline of $\simeq 658$ km.

In this first discussion, we focused on the possibility to measure the θ_{13} and δ_{CP} parameters. Our strategy is based on the precise measurement of the energy spectrum of the oscillated events, and in particular on the comparison of the features of 1st maximum oscillation peak with those of the 2nd maximum oscillation peak. In order to efficiently determine and study those features, we rely on the excellent neutrino event reconstruction and incoming neutrino energy resolution, as is expected in the case of the fully-sensitive and fine charge imaging capabilities of the liquid Argon TPC.

Beyond this case study, we intend to perform more detailed simulations of the performance of the experiment including for example different sources of systematic errors and sources of backgrounds which have been up-to-now neglected.

The construction and operation of a 100 kton liquid Argon TPC certainly represents a technological challenge at the present state of knowledge of the technique. For it to become a realistic option, we stress the importance and necessity of further R&D and of dedicated experimental measurement campaigns. At this stage, we intend to pursue our investigations on a ton-scale prototype based on the novel double-phase readout imaging method. Options to operate small devices in the J-PARC neutrino beam are being assessed in parallel. In addition, we have started to address the possibility of an "intermediate" prototype, presumably in the range of 1 kton of mass, based on a similar but scaled down design of the potential 100 kton detector.

Acknowledgements

References

[1] G. Steigman Ann.Rev.Astron.Astrophys, 14(1976)339; A.D. Sakharov Pisma Zh.ETF 5(1967)32.

[2] Y. Itow *et al.*, "The JHF-Kamioka neutrino project," arXiv:hep-ex/0106019.

[3] M. Apollonio *et al.* [CHOOZ Collaboration], "Limits on neutrino oscillations from the CHOOZ experiment," Phys. Lett. B **466**, 415 (1999)

[4] T. Hasegawa, Talk given at the 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08). Slides available at `http://j-parc.jp/NP08/`

[5] J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. Mena, "On the measurement of leptonic CP violation," Nucl. Phys. B **608**, 301 (2001) [arXiv:hep-ph/0103258].

[6] H. Minakata and H. Nunokawa, "Exploring neutrino mixing with low energy superbeams," JHEP **0110**, 001 (2001) [arXiv:hep-ph/0108085].

[7] V. Barger, D. Marfatia and K. Whisnant, "Breaking eight-fold degeneracies in neutrino CP violation, mixing, and mass hierarchy," Phys. Rev. D **65**, 073023 (2002) [arXiv:hep-ph/0112119].

[8] W. J. Marciano, "Extra long baseline neutrino oscillations and CP violation," arXiv:hep-ph/0108181.

[9] M. V. Diwan *et al.*, "Very long baseline neutrino oscillation experiments for precise measurements of mixing parameters and CP violating effects," Phys. Rev. D **68** (2003) 012002 [arXiv:hep-ph/0303081].

[10] M. Ishitsuka, T. Kajita, H. Minakata and H. Nunokawa, "Resolving neutrino mass hierarchy and CP degeneracy by two identical detectors with different baselines," Phys. Rev. D **72**, 033003 (2005) [arXiv:hep-ph/0504026].

[11] K. Hagiwara, N. Okamura and K. i. Senda, "Physics potential of T2KK: An extension of the T2K neutrino oscillation experiment with a far detector in Korea," Phys. Rev. D **76**, 093002 (2007) [arXiv:hep-ph/0607255].

[12] A. Meregaglia and A. Rubbia, "Neutrino Oscillations With A Next Generation Liquid Argon TPC Detector in Kamioka or Korea Along The J-PARC Neutrino Beam," arXiv:0801.4035 [hep-ph].

[13] S. Amerio *et al.*, "Design, construction and tests of the ICARUS T600 detector", Nucl. Instrum. Meth. A 527 (2004) 329 and references therein.

[14] A. Rubbia, "Experiments for CP-violation: A giant liquid argon scintillation, Cerenkov and charge imaging experiment?," arXiv:hep-ph/0402110.

[15] A. Rubbia, "ArDM: A ton-scale liquid argon experiment for direct detection of dark matter in the universe," J. Phys. Conf. Ser. **39** (2006) 129 [arXiv:hep-ph/0510320].

[16] A. Marchionni, Talk given at the 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08). Slides available at `http://j-parc.jp/NP08/`

[17] A. Meregaglia and A. Rubbia, "Neutrino oscillation physics at an upgraded CNGS with large next generation liquid argon TPC detectors," JHEP **0611**, 032 (2006) [arXiv:hep-ph/0609106].

[18] M. Freund, "Analytic approximations for three neutrino oscillation parameters and probabilities in matter," Phys. Rev. D **64**, 053003 (2001) [arXiv:hep-ph/0103300].

[19] A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. Mena and S. Rigolin, "Golden measurements at a neutrino factory," Nucl. Phys. B **579**, 17 (2000) [Erratum-ibid. B **593**, 731 (2001)] [arXiv:hep-ph/0002108].

[20] http://nuint.ps.uci.edu/nuance/

[21] F. Arneodo *et al.* [ICARUS-Milano Collaboration], "Performance of a liquid argon time projection chamber exposed to the WANF neutrino beam," Phys. Rev. D **74**, 112001 (2006) [arXiv:physics/0609205].

[22] R. Brun *et al.*, GEANT3 Reference Manual,. CERN Program Library Long Writeup. W5013, DD/EE/84-1, 1987. For hadronic secondary interactions, we select GFLUKA.

[23] L. Wolfenstein, "Neutrino oscillations in matter," Phys. Rev. D **17** (1978) 2369.

[24] C.Andreopoulos, Nucl.Phys.B Proc.Suppl. 159:217-222, 2006; C.Andreopoulos, Act.Phys.Pol.B Vol.37,8:2349, 2006

[25] J. C. Pati and A. Salam, "Unified Lepton-Hadron Symmetry And A Gauge Theory Of The Basic Interactions," Phys. Rev. D **8**, 1240 (1973).

[26] H. Georgi and S. L. Glashow, "Unity Of All Elementary Particle Forces," Phys. Rev. Lett. **32**, 438 (1974).

[27] A. Bueno *et al.*, "Nucleon decay searches with large liquid argon TPC detectors at shallow depths: Atmospheric neutrinos and cosmogenic backgrounds," JHEP **0704**, 041 (2007) [arXiv:hep-ph/0701101].